



# Kaon decay at rest neutrinos sources for sterile neutrino studies

Joshua Spitz, MIT  
4/17/2013

Snowmass Workshop on Intensity Frontier, BNL

# Outline

- Sterile neutrinos
- KDAR (kaon decay-at-rest)
- piDAR (pion decay-at-rest)
- Beam considerations for piDAR+KDAR

# Outline

- Sterile neutrinos
- KDAR (kaon decay-at-rest)
- piDAR (pion decay-at-rest)
- Beam considerations for piDAR+KDAR

# The neutrino oscillation picture

Atmospheric neutrinos  
Solar neutrinos  
Accelerator neutrinos  
Reactor neutrinos



Well established  
oscillations

- Almost all of the oscillation results fit nicely within the three neutrino picture (two mass splittings and three mixing angles).
- Neutrinos from different sources are oscillating according to the same rulebook!

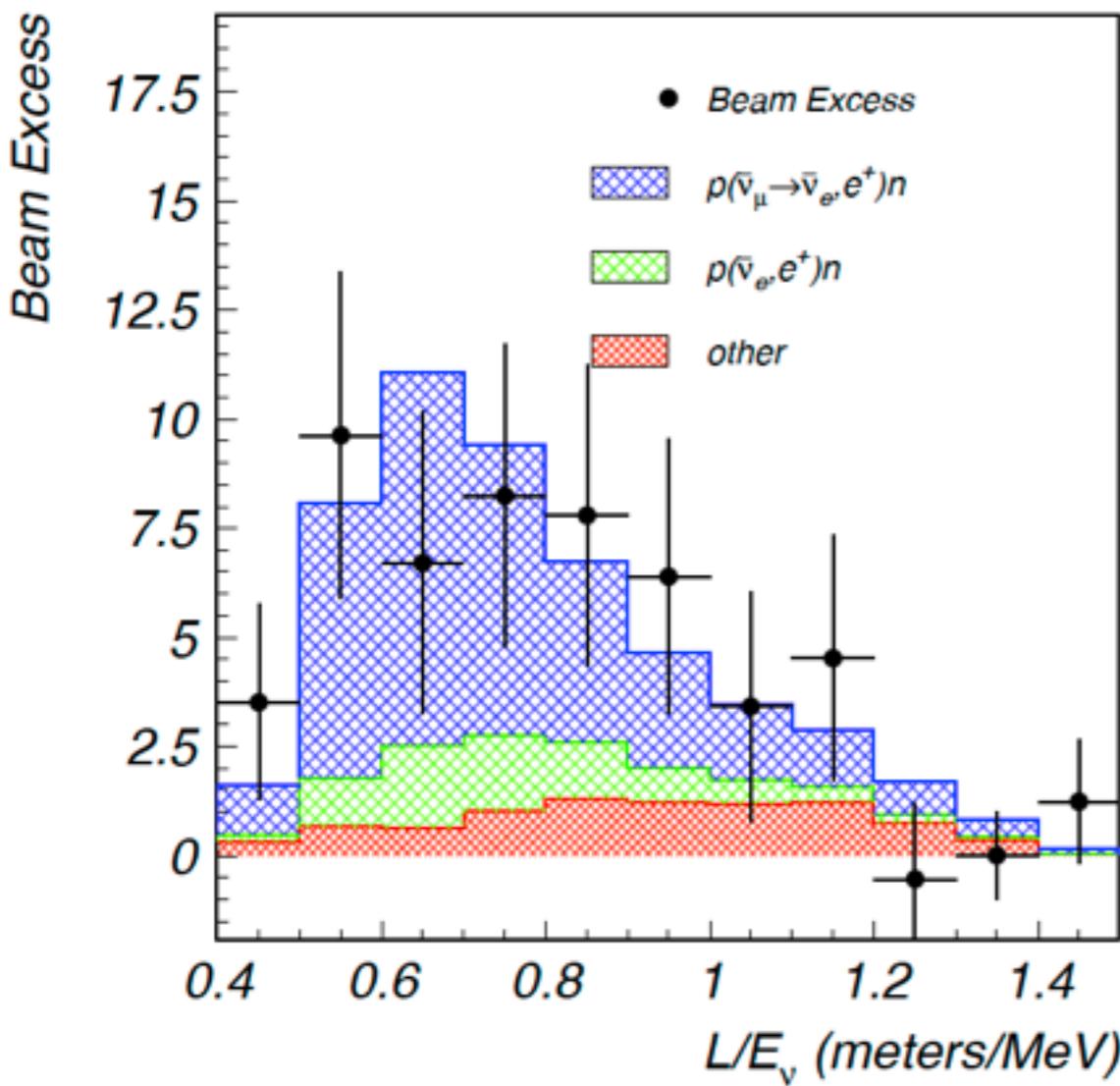
The three neutrino oscillation  
picture works extraordinarily well.

But, there are some anomalies that don't fit.



# The Liquid Scintillator Neutrino Detector anomaly

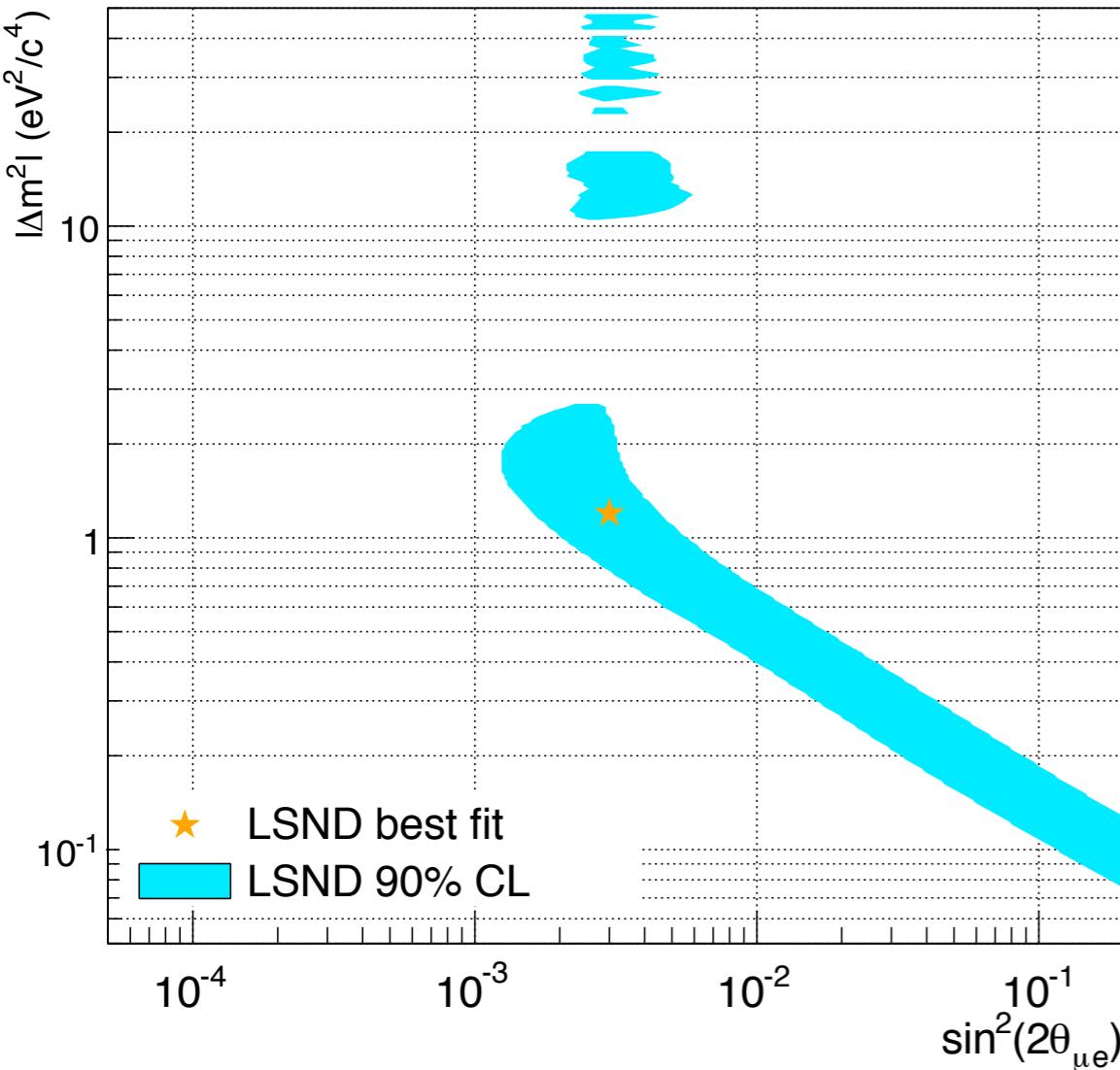
Antineutrinos from an accelerator seem to appear!



- LSND observed  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  at  $3.8\sigma$  significance with  $\Delta m^2 \sim 1 \text{ eV}^2$ .

# The Liquid Scintillator Neutrino Detector anomaly

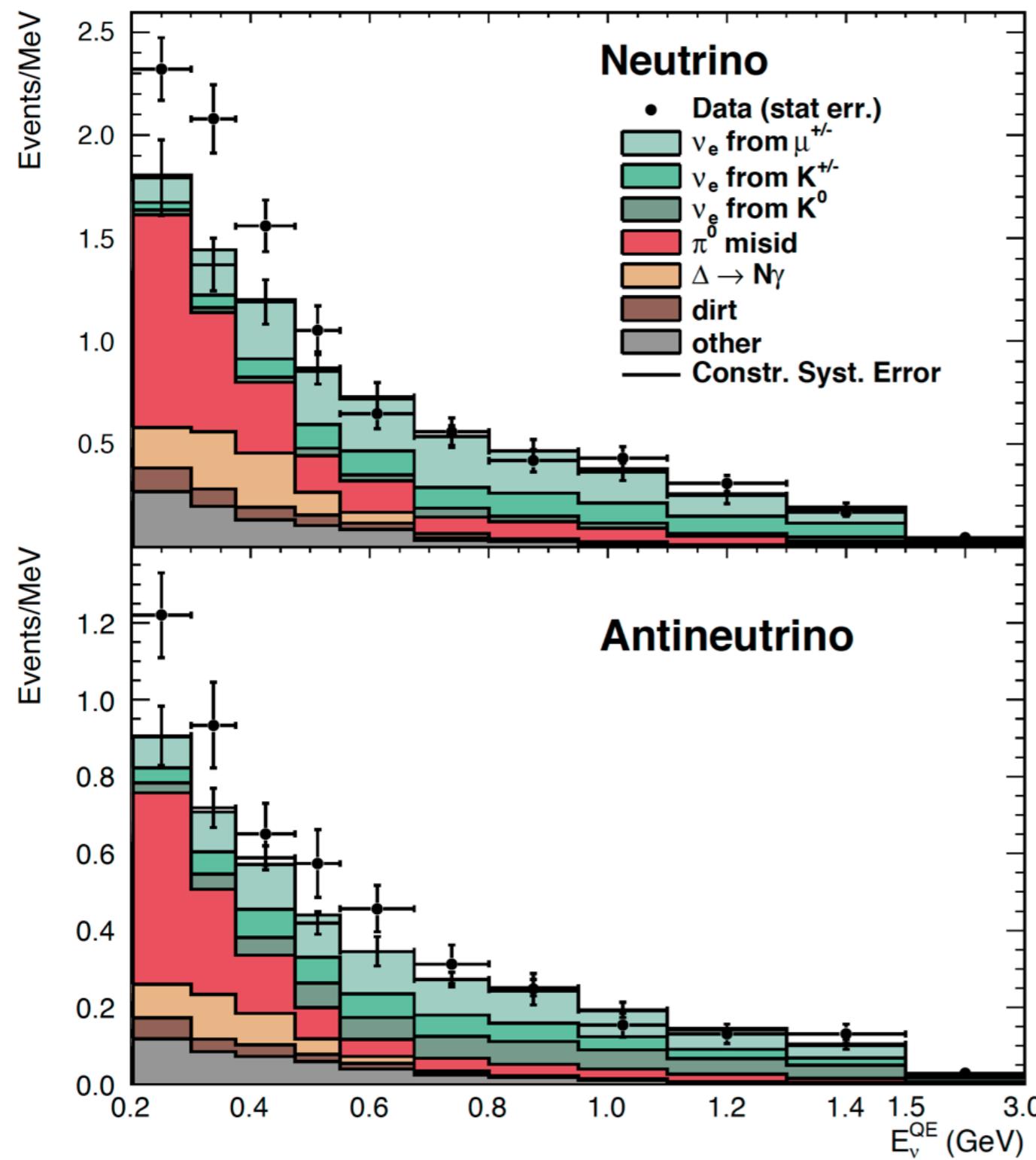
Antineutrinos from an accelerator seem to appear!



- LSND observed  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  at  $3.8\sigma$  significance with  $\Delta m^2 \sim 1 \text{ eV}^2$ .
- That's odd. There are two independent mass splittings in the three neutrino picture and they are precisely measured.

$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2)$$

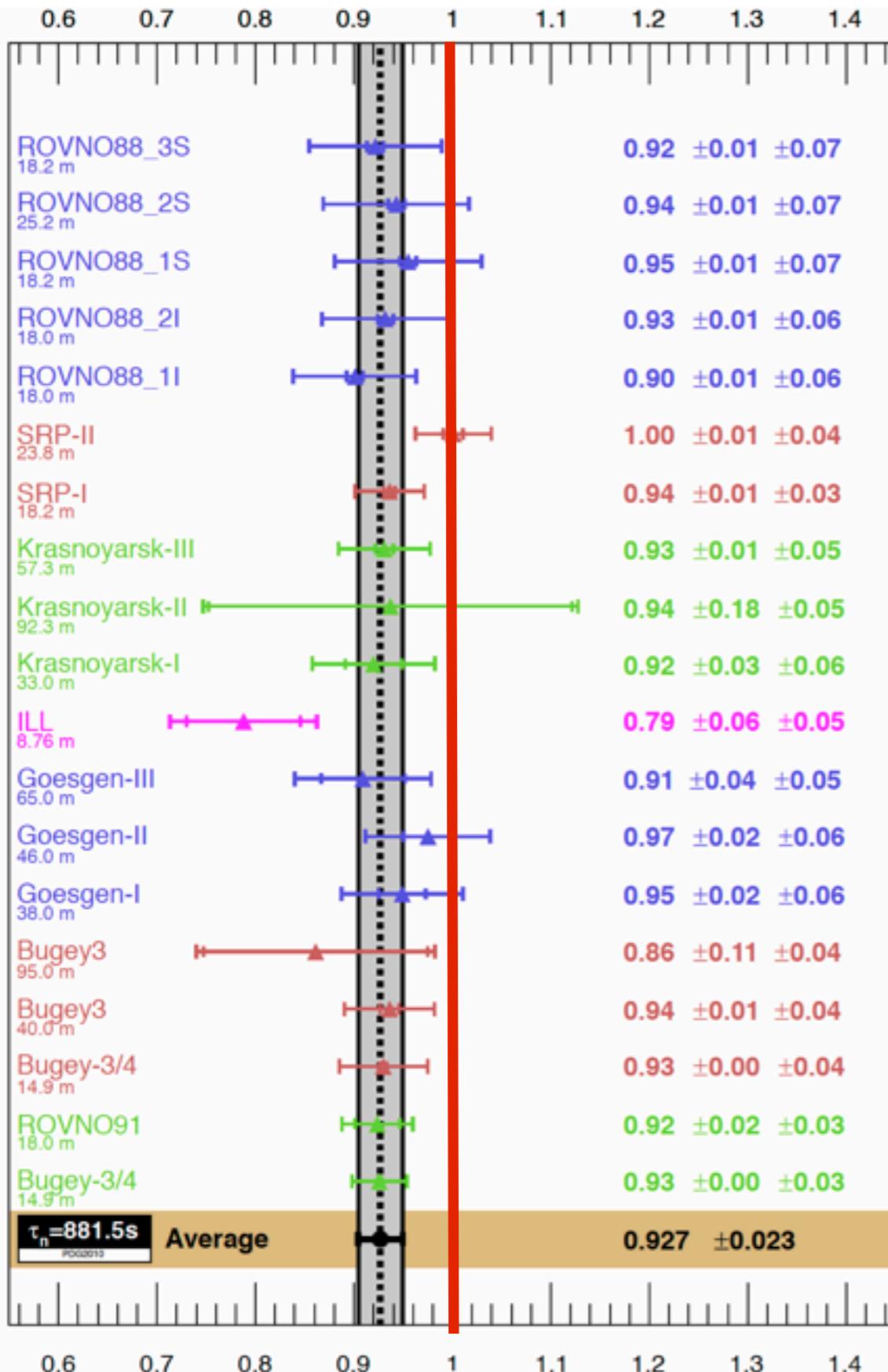
# The MiniBooNE anomalies



$$\nu_\mu \rightarrow \nu_e$$

Neutrinos and antineutrinos from an accelerator seem to appear!

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



# The reactor anomaly

Reactor antineutrinos seem to disappear!

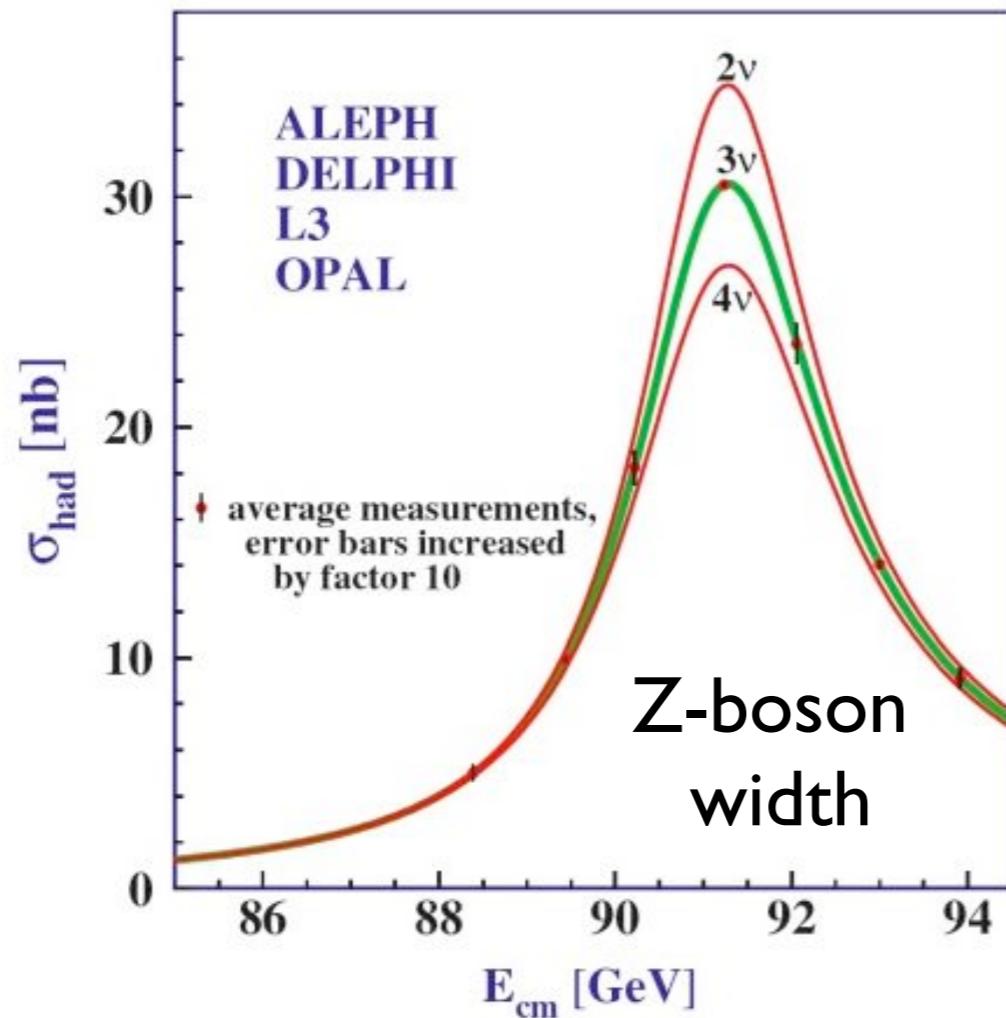
$$\bar{\nu}_e \rightarrow \bar{\nu}_x$$

$0.927 \pm 0.023$

observed/expected antineutrino rate

# If it exists, what is the sterile neutrino?

- Sterile equals no standard model interactions.

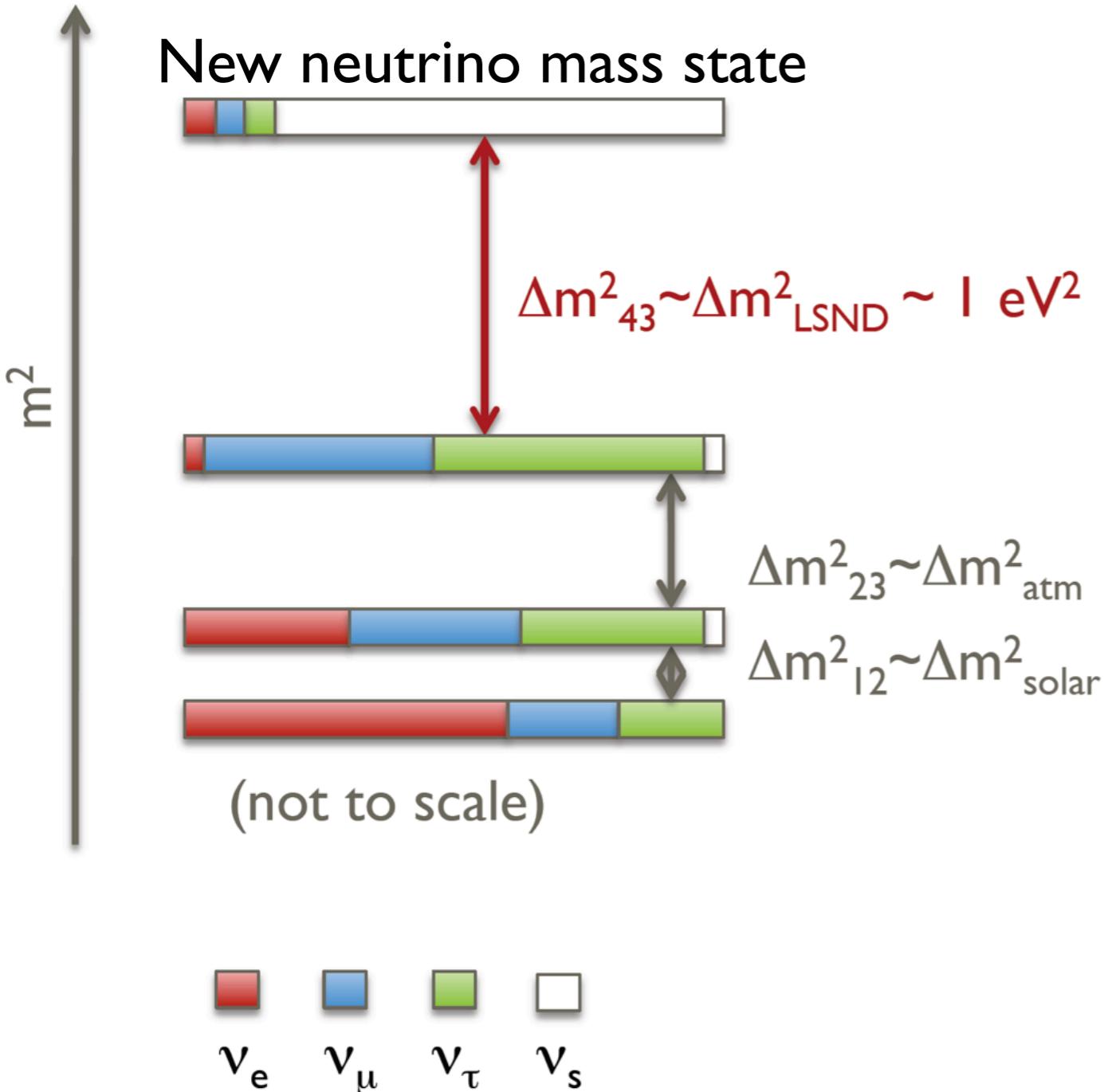


We know the Z boson decays into three neutrinos.

- Can participate in oscillations with active flavors.

$$\nu_e \rightarrow \nu_s , \quad \nu_\mu \rightarrow \nu_s , \quad \nu_\tau \rightarrow \nu_s$$

# Where does it fit?



- The observation of neutrino mass implies that there can be sterile, right-handed neutrinos. So, this is not unexpected.
- A light sterile neutrino would have profound effects on:
  - Radiation density in the early universe.
  - Supernova evolution.
  - Possible warm dark matter candidate?
  - Active neutrino oscillations and particle physics in general.

# Present status

- A number of experiments hint at a new neutrino mass eigenstate around 1 eV.
- A definitive probe of the sterile neutrino is necessary.

If (neutrino) history has taught us anything it is this:

Pursue experimental anomalies

# Outline

- Sterile neutrinos
- KDAR (kaon decay-at-rest)
- piDAR (pion decay-at-rest)
- Beam considerations for piDAR+KDAR

# How to probe the sterile neutrino?

1. Make a lot of neutrinos\*.
2. Count them.
3. Compare to how many you expected.

# How to probe the sterile neutrino?

1. Make a lot of neutrinos\*.
2. Count them.
3. Compare to how many you expected.

\*Choose a smart baseline ( $L$ ) and energy ( $E$ ) so that you are probing the relevant oscillation parameter space ( $\Delta m^2, \theta$ ).

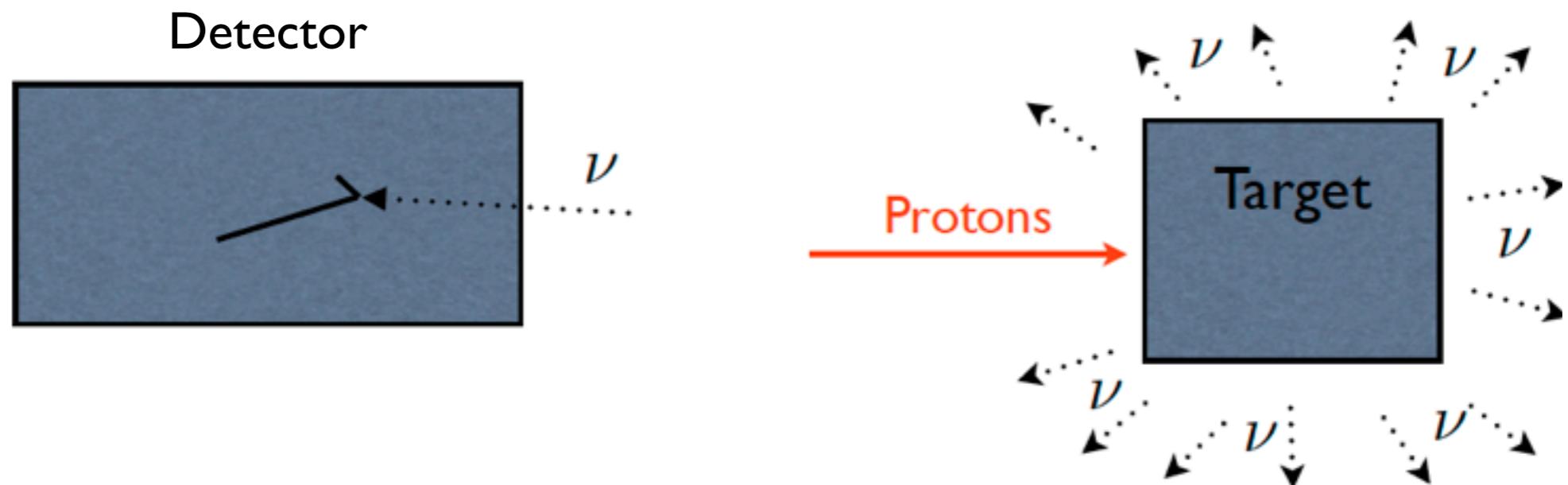
$$P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left( 1.267 \frac{\Delta m^2 L}{E} \frac{\text{GeV}}{\text{eV}^2 \text{km}} \right)$$

e.g.  $\frac{L}{E} \sim 1 \frac{\text{m}}{\text{MeV}}$  probes  $\Delta m^2 \sim 1 \text{ eV}^2$

# A sterile neutrino search w/ kaon decay at rest

J. Spitz, PRD 85 093020 (2012)

$$\nu_\mu \rightarrow \nu_e ?$$



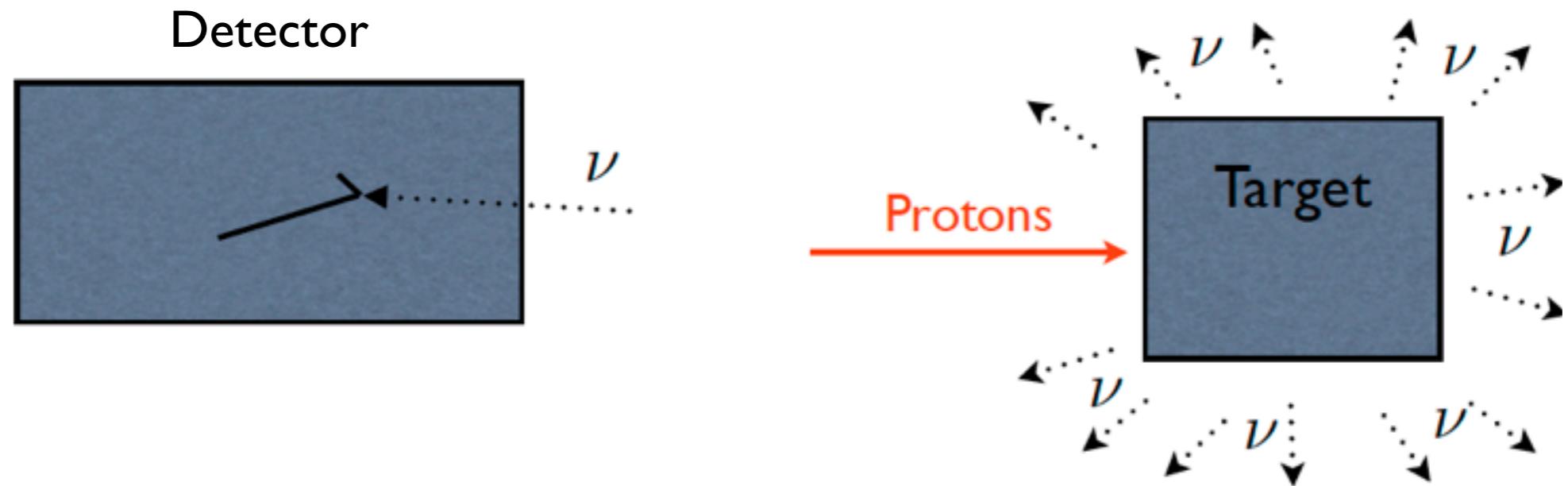
Monoenergetic (235 MeV) neutrino!

$$K^+ \rightarrow \mu^+ \nu_\mu$$

# A sterile neutrino search w/ kaon decay at rest

J. Spitz, PRD 85 093020 (2012)

$$\nu_\mu \rightarrow \nu_e ?$$



Monoenergetic (235 MeV) neutrino!

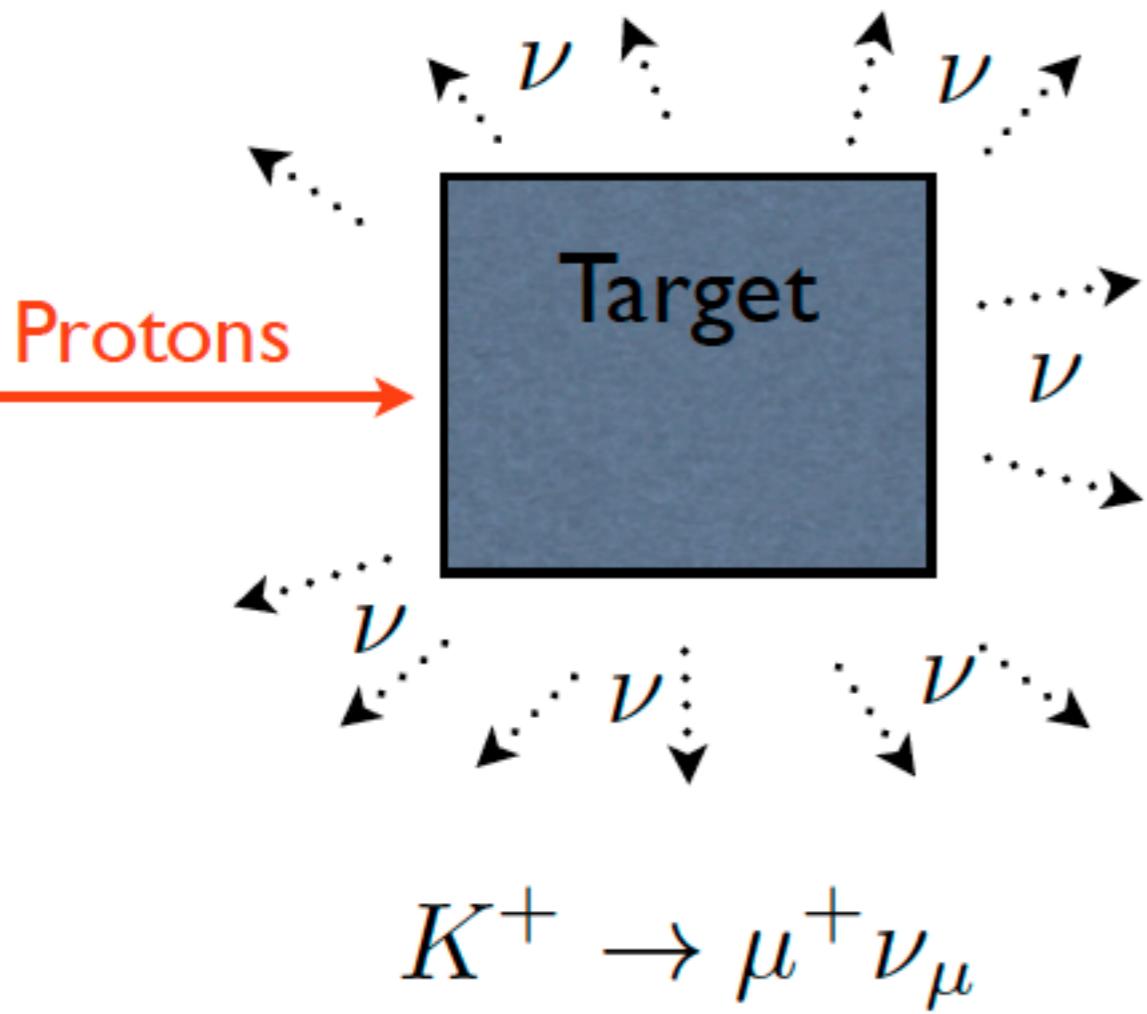
Backgrounds {

$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

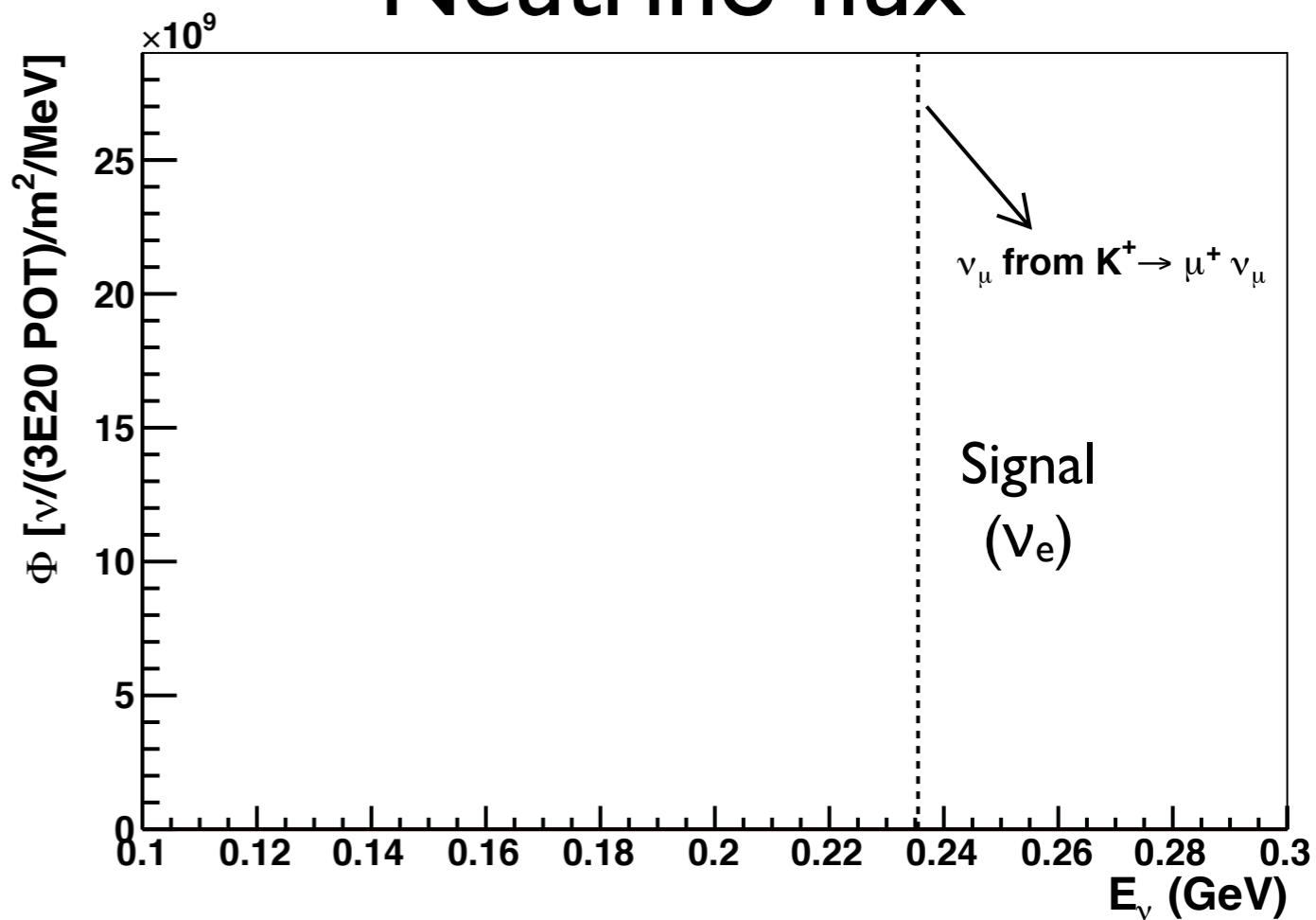
$$K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$$

# A sterile neutrino search w/ kaon decay at rest

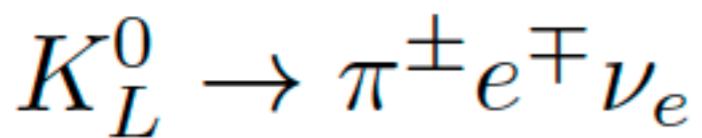
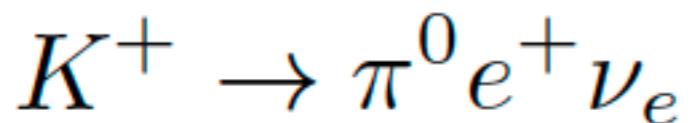
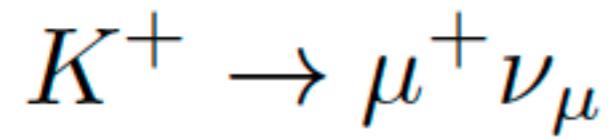
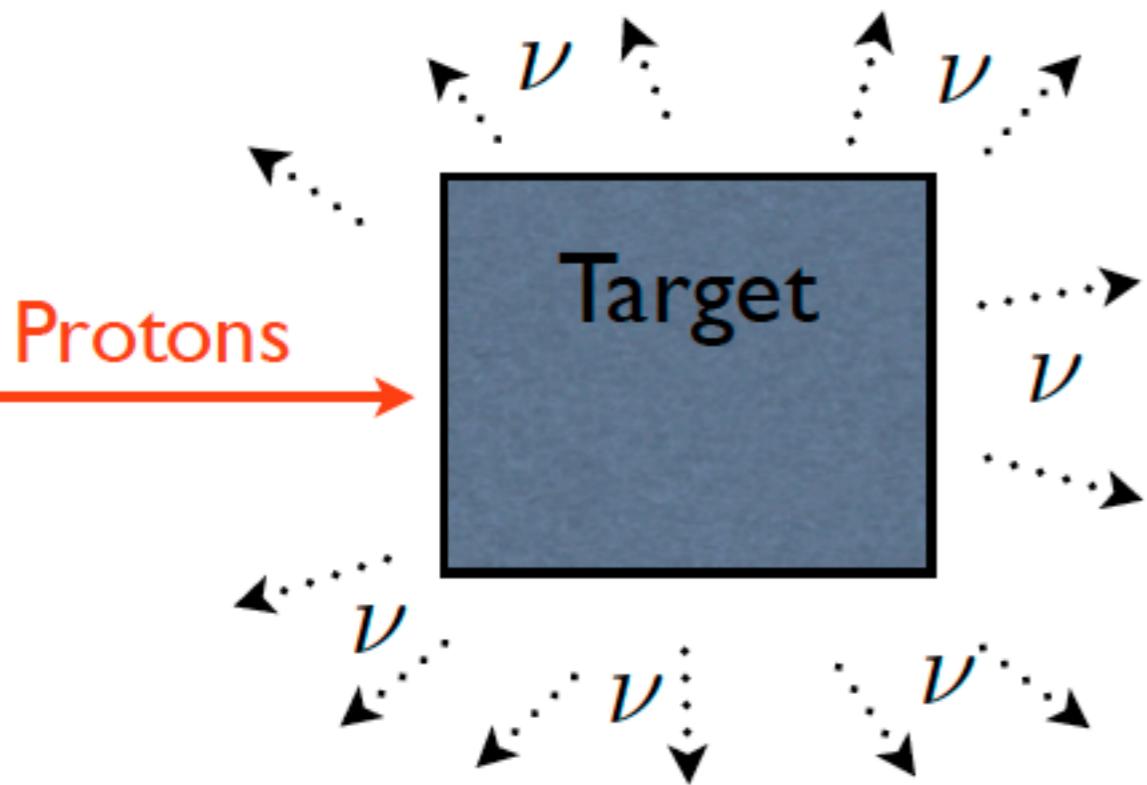


$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino flux

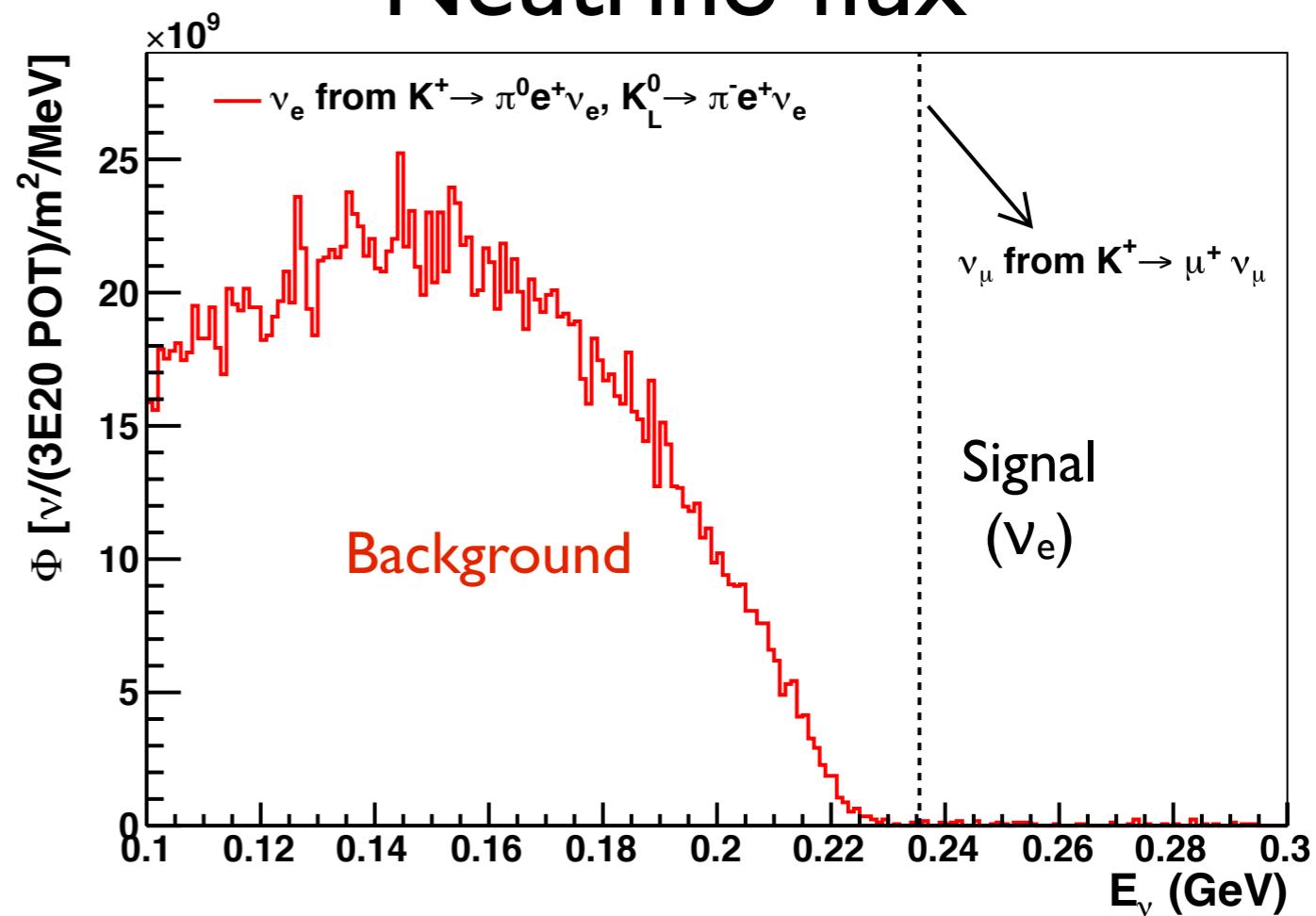


# A sterile neutrino search w/ kaon decay at rest



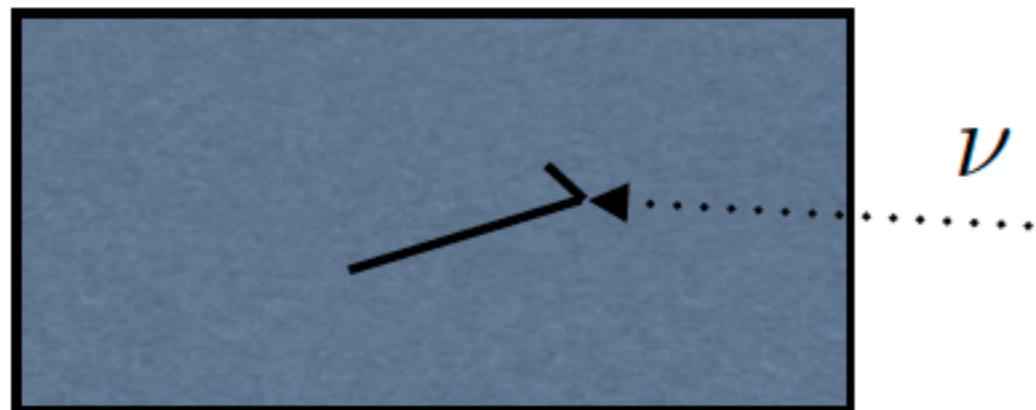
$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino flux



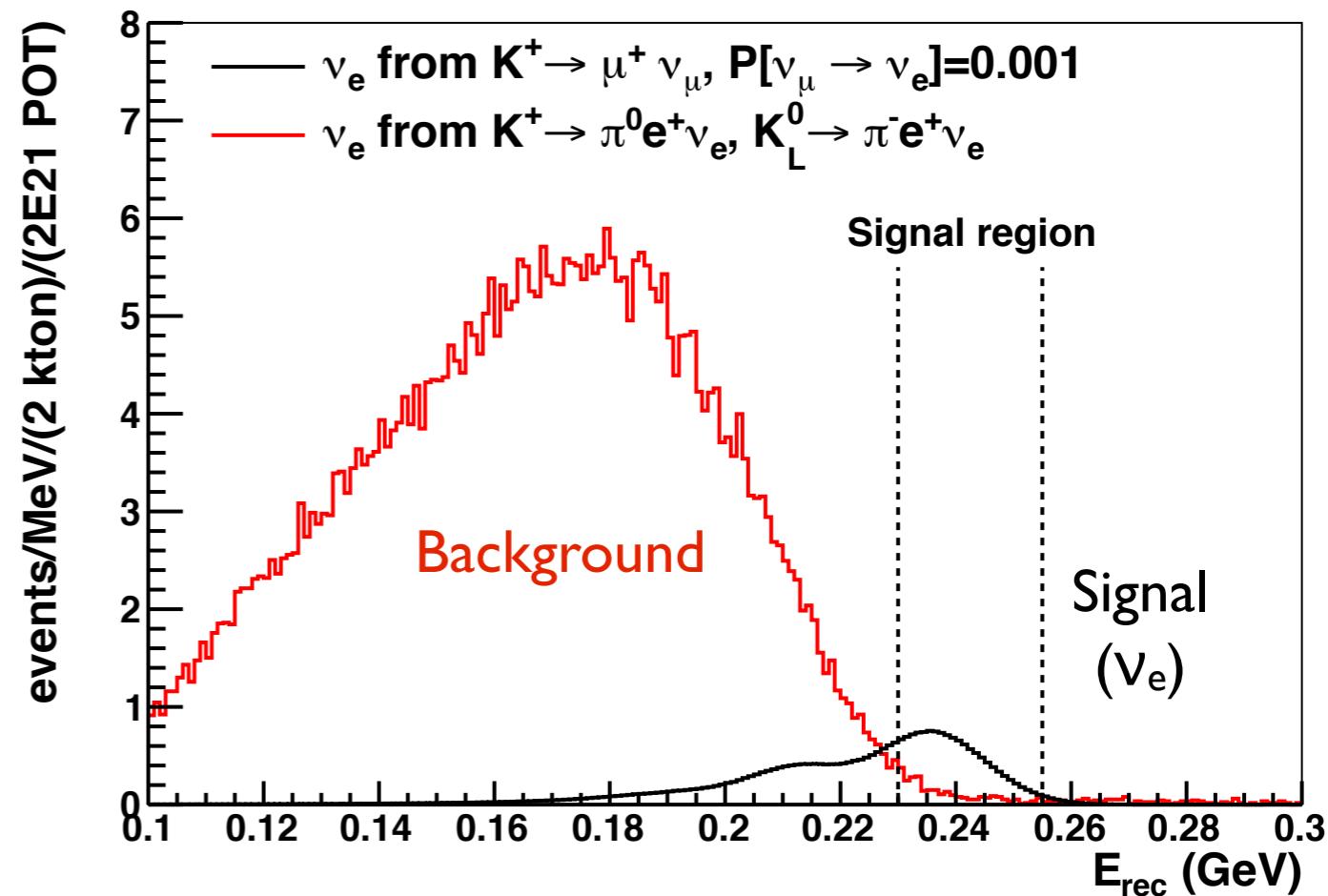
# A sterile neutrino search w/ kaon decay at rest

Detector



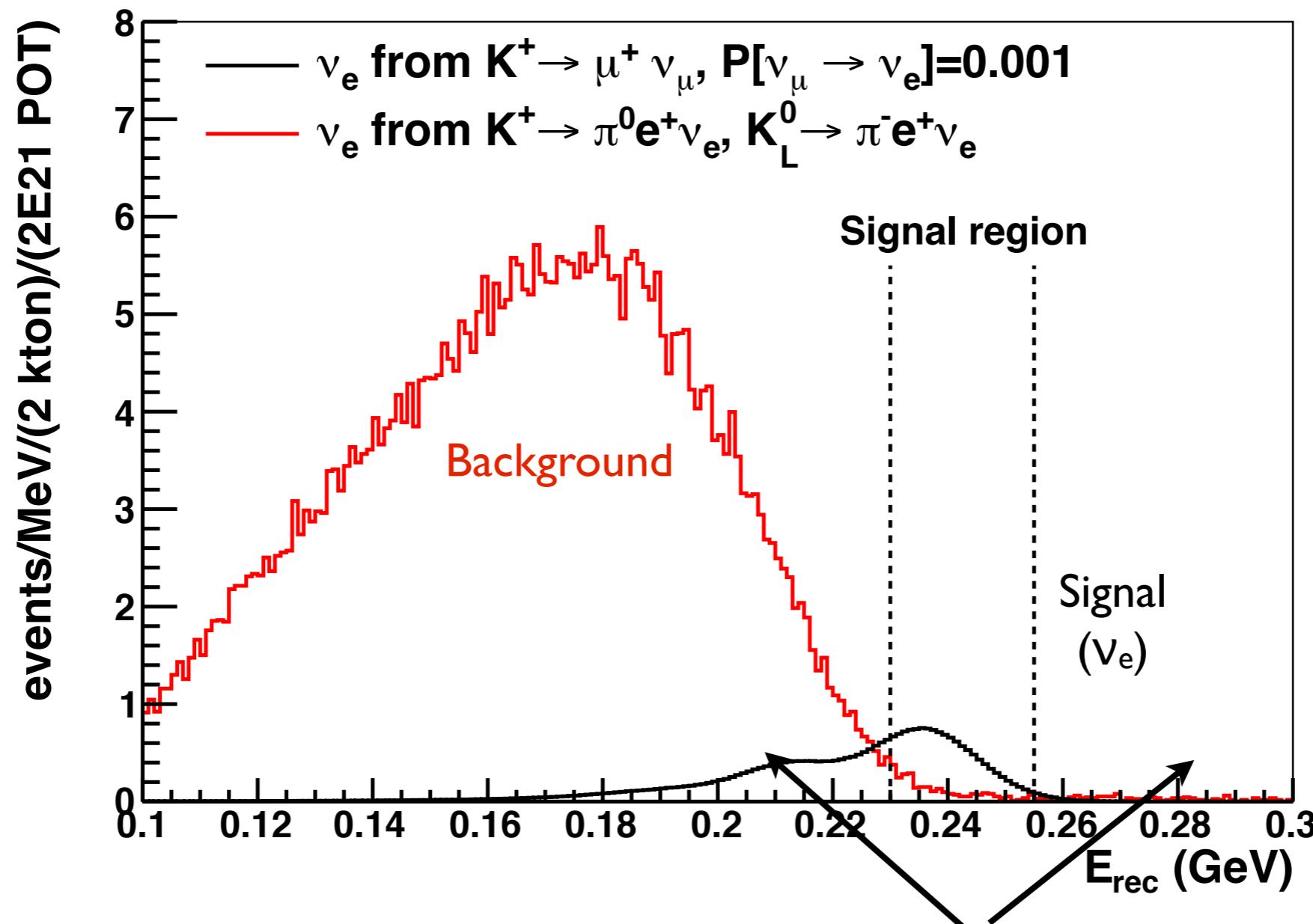
$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino rate



- The concept is analogous to a neutrinoless double beta decay search.
- You look for an excess near the endpoint of a well understood and measured background distribution.

# Background prediction is *in-situ*



Identify a signal region and measure background in sidebands

# KDAR requirements

- A lot of protons ( $>3$  GeV)
- A big detector
- Energy resolution

That's the original “KDAR” idea.

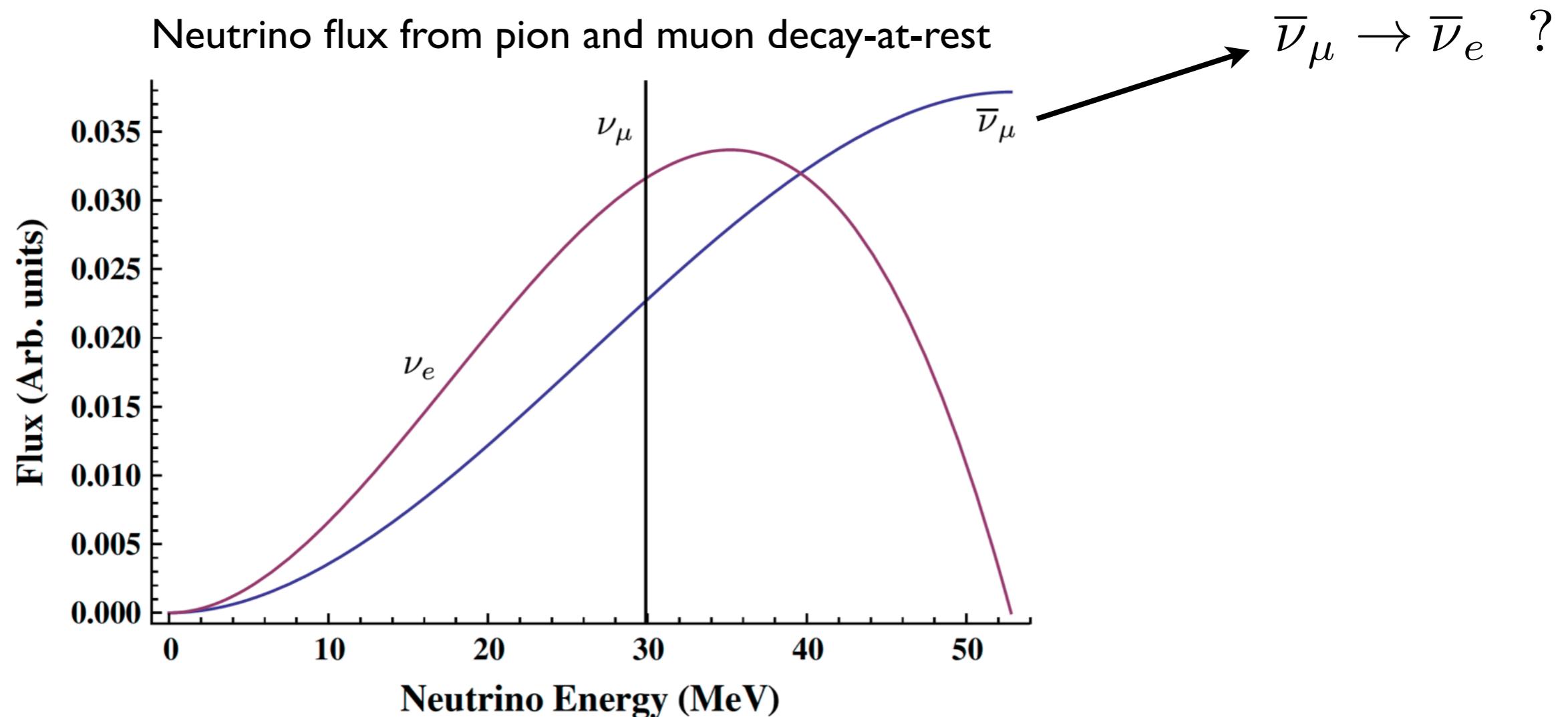
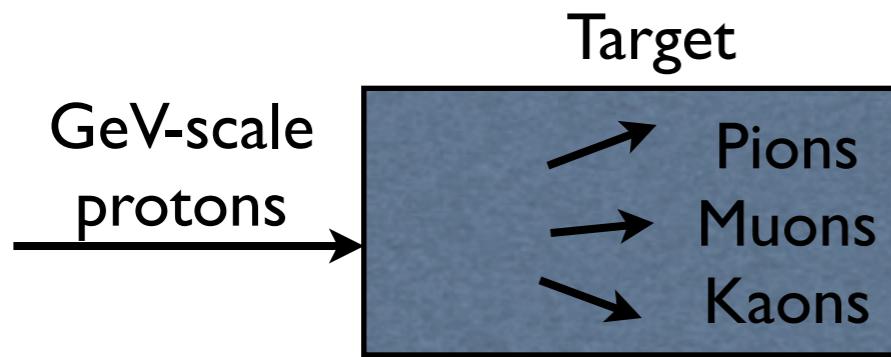
....

However, it turns out that you can also do  
LSND-like “piDAR” with the same experiment!

# Outline

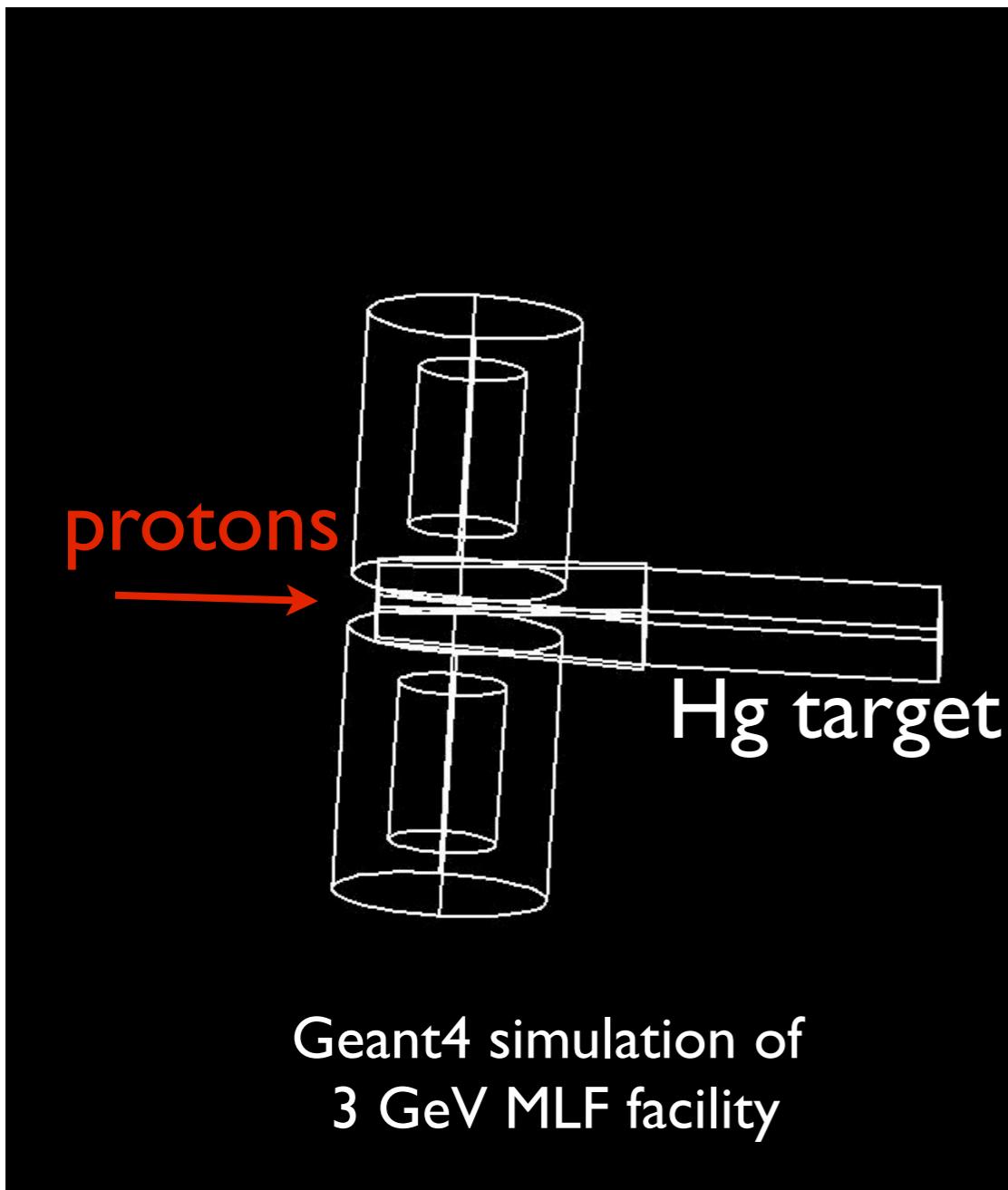
- Sterile neutrinos
- KDAR (kaon decay-at-rest)
- piDAR (pion decay-at-rest)
- Beam considerations for piDAR+KDAR

# “piDAR” (LSND-like)

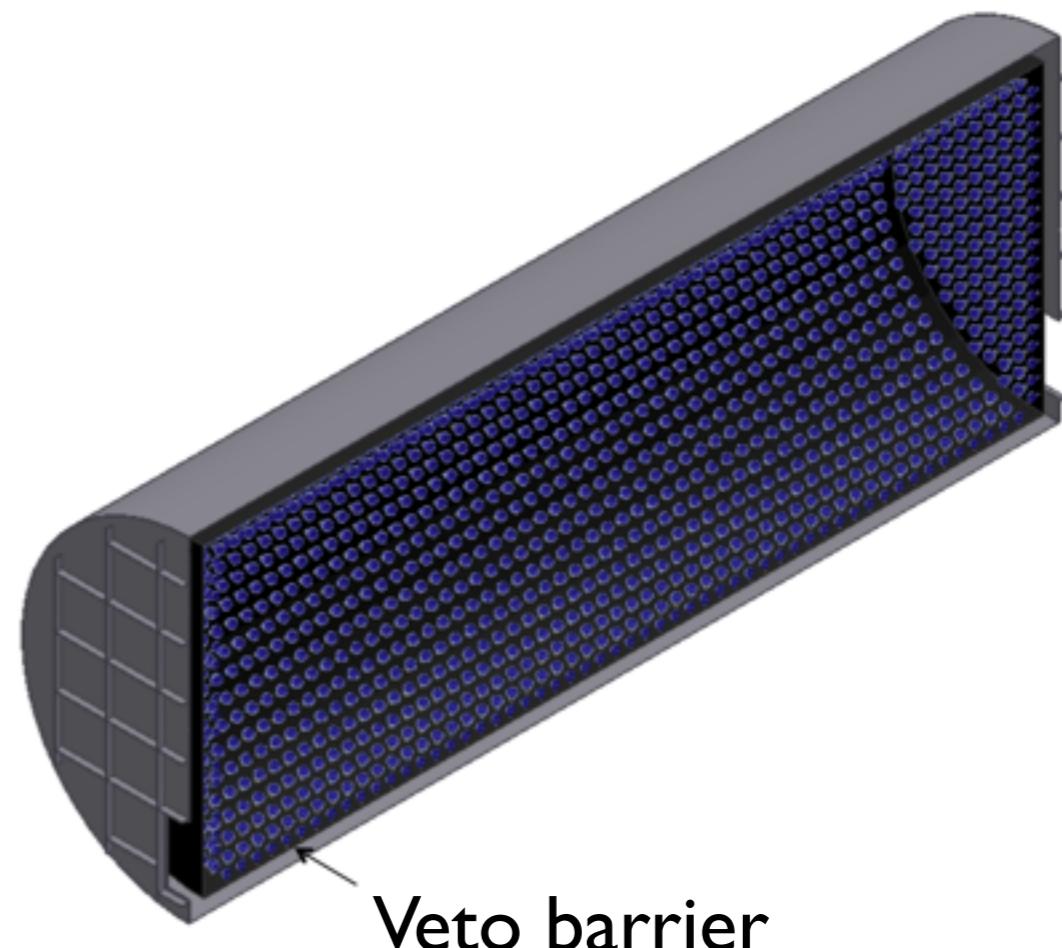


# piDAR + KDAR

## Neutrino source



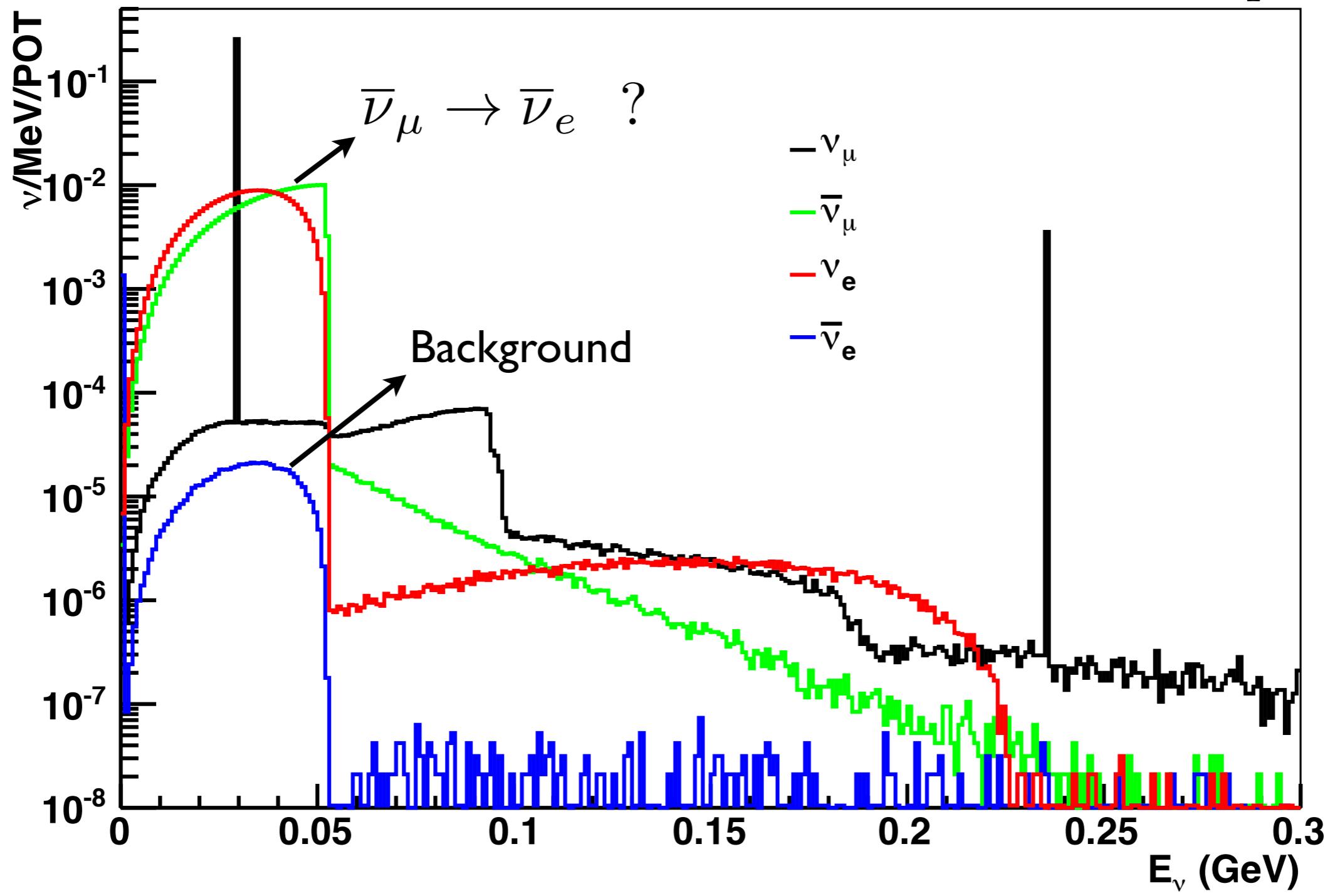
**Liquid scintillator detector**  
(piDAR requires free protons for  $\bar{\nu}_e p \rightarrow e^+ n$ )



Detector parameters are under  
consideration (baseline, active volume, etc.)

# piDAR

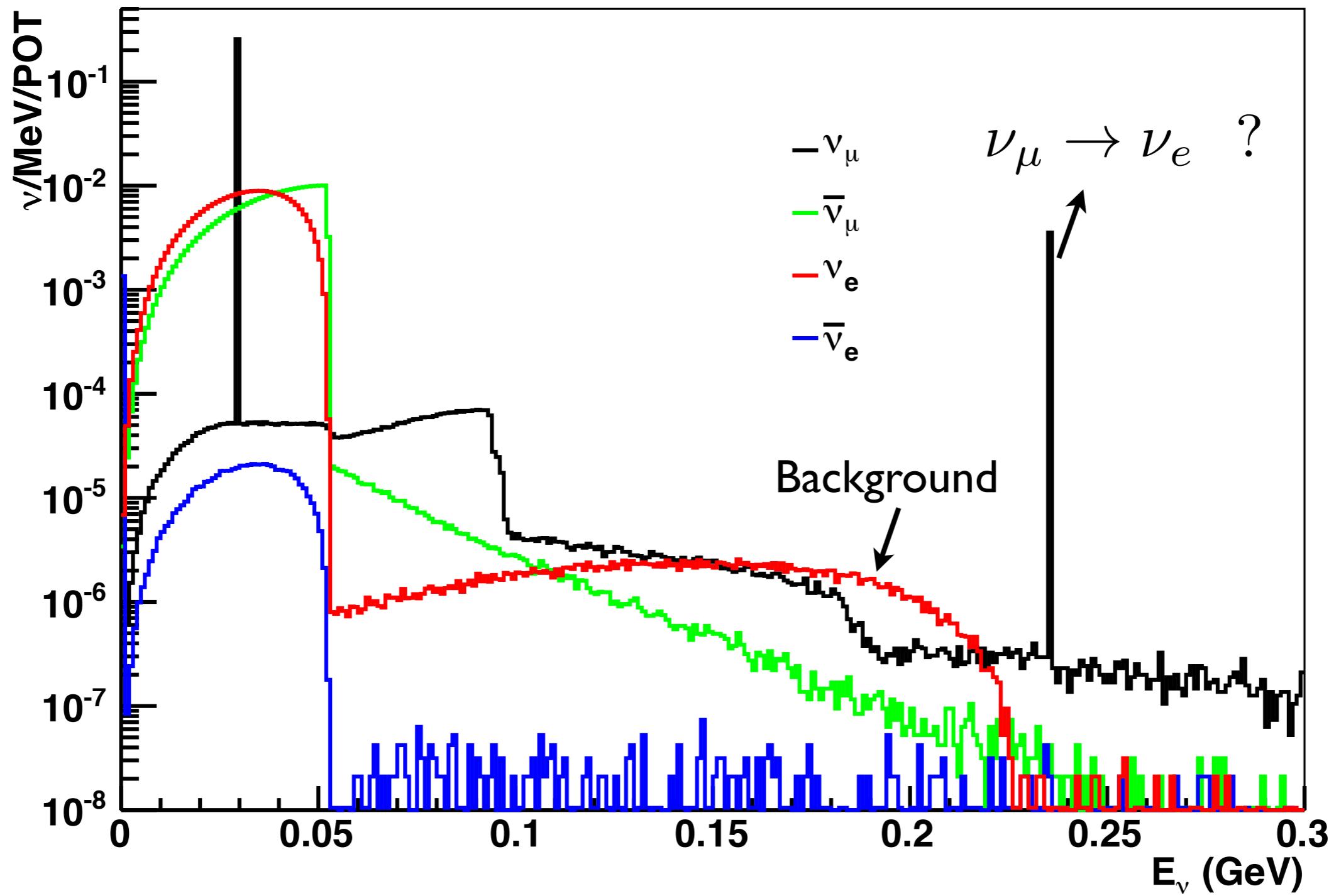
Detect with:  
 $\bar{\nu}_e p \rightarrow e^+ n$



Simulated flux @ MLF facility

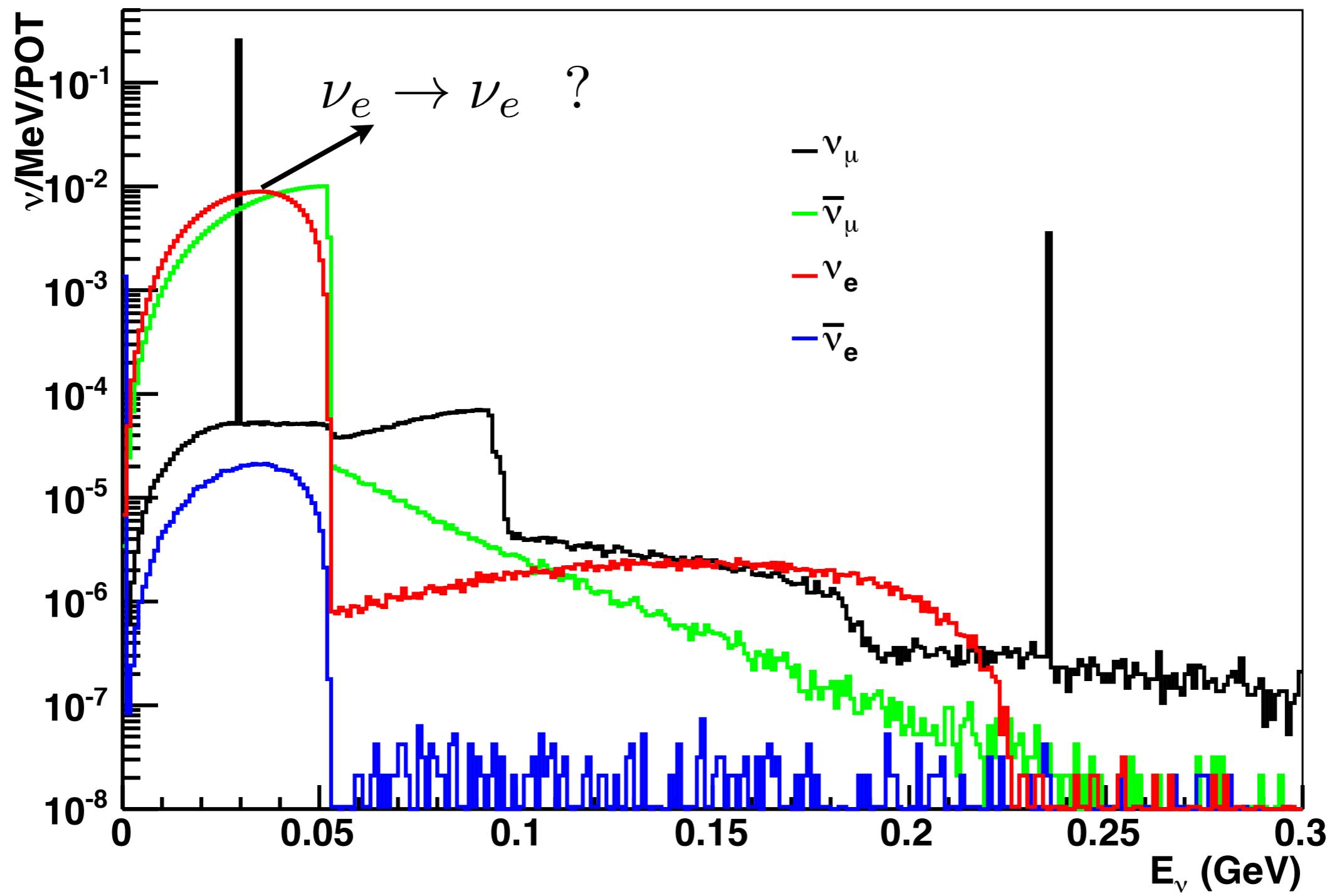
# KDAR

Detect with:  
 $\nu_e n \rightarrow e^- p$



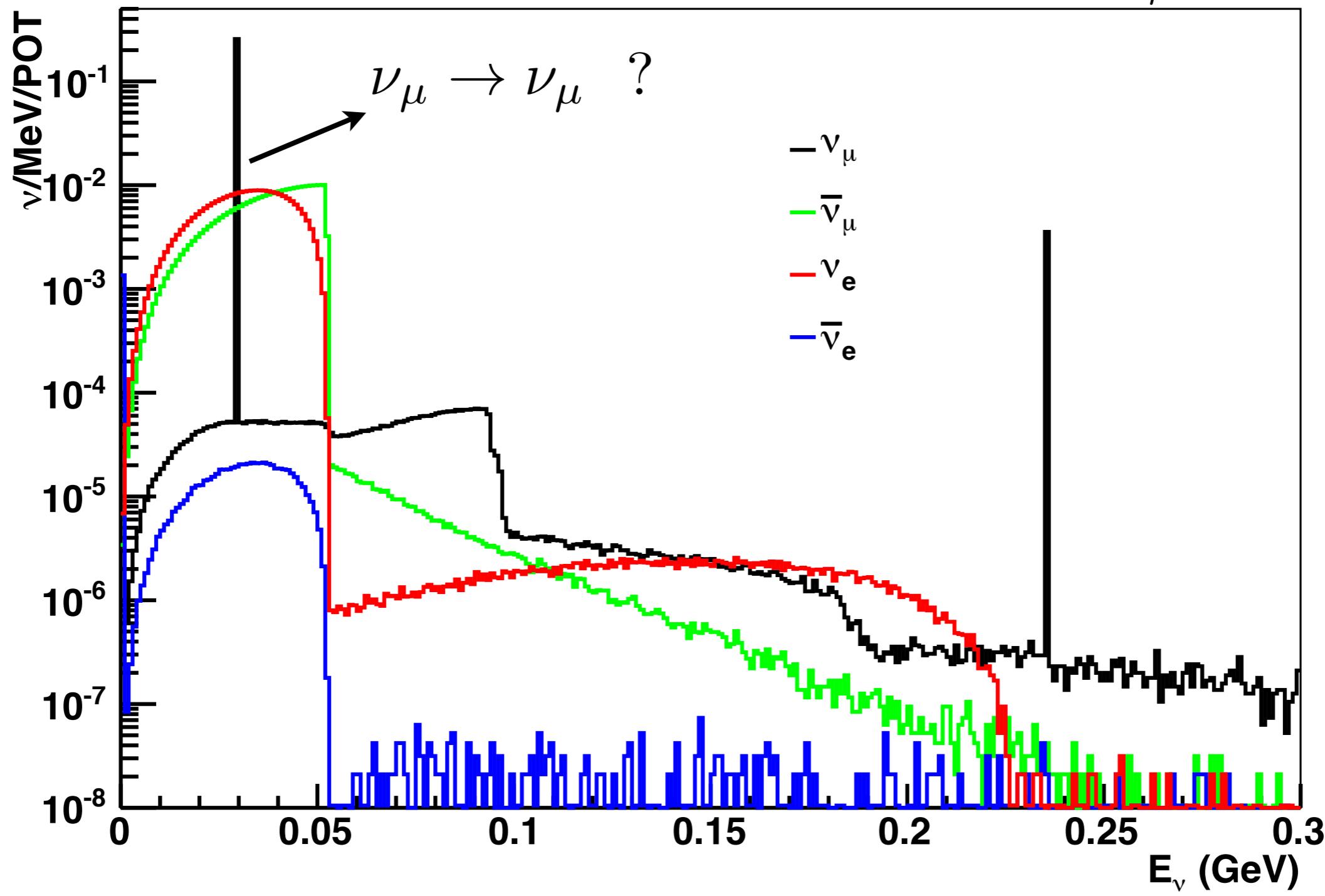
Simulated flux @ MLF facility

**Detect with:**  
 $\nu_e \ ^{12}C \rightarrow e^- \ ^{12}N_{gs}$



Simulated flux @ MLF facility

**Detect with:**  
 $\nu_\mu \ ^{12}C \rightarrow \nu_\mu \ ^{12}C^*$

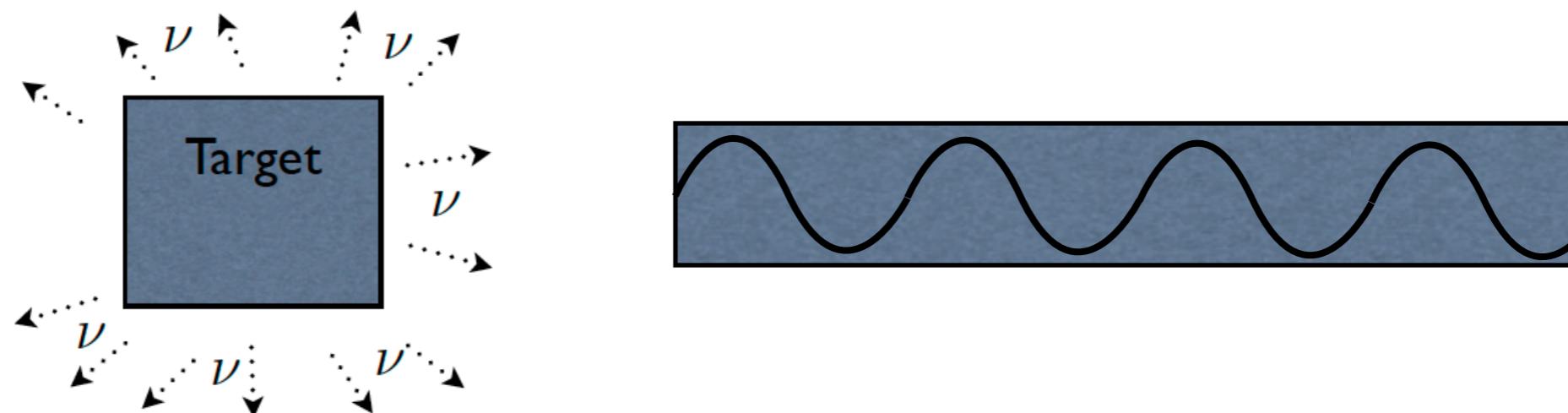


Simulated flux @ MLF facility

# Thinking about experimental parameters

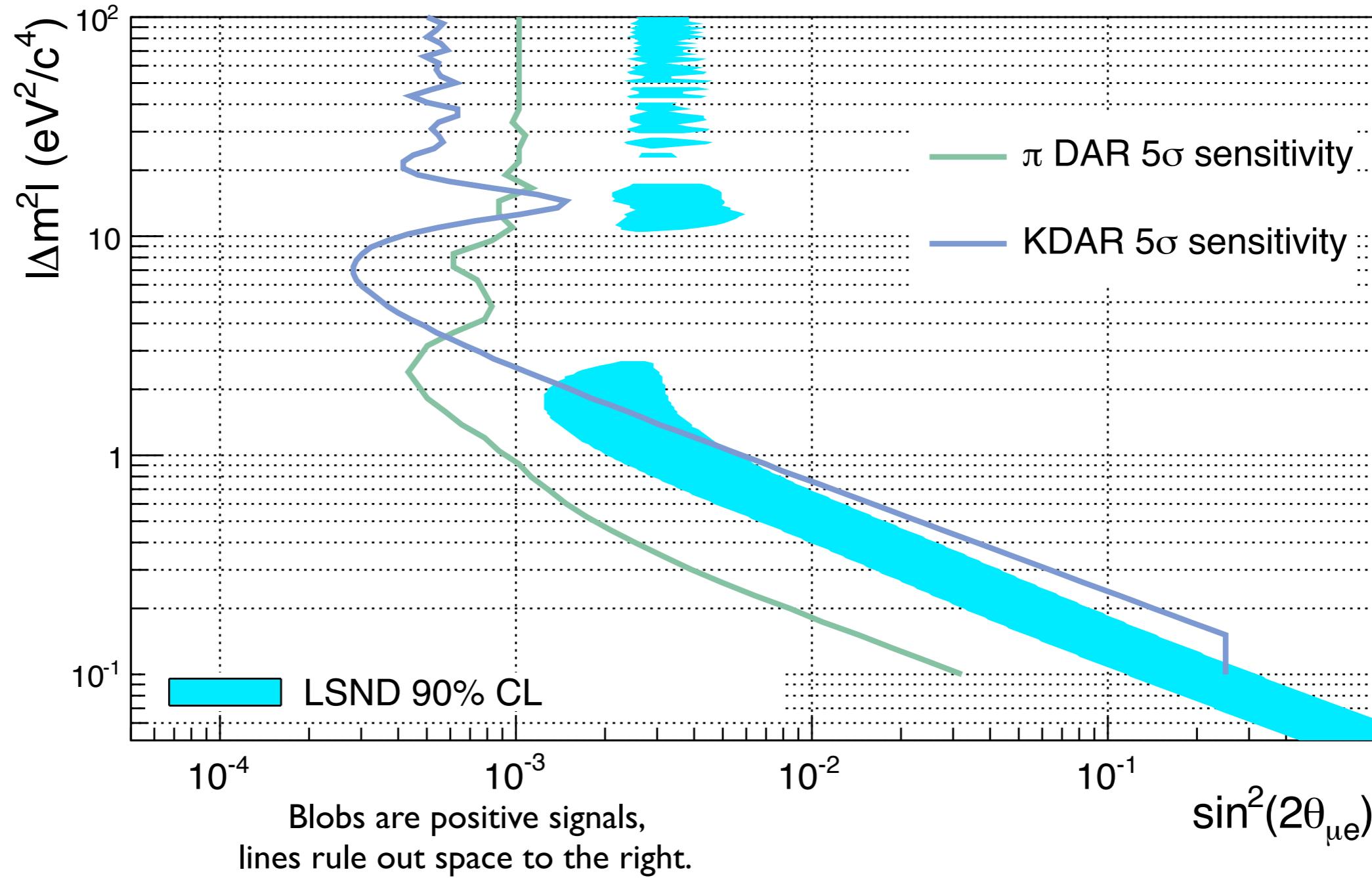
Example I:

A very long and close ( $\sim 40$  m) detector  
Advantage: optimized for piDAR; can potentially observe the L/E oscillation wave



(Sensitivity to  $\Delta m^2 \sim 1$  eV $^2$  is optimized at 40-60 m for piDAR and  $\sim 160$  m for KDAR)

Example I:  
 5 year, 1 MW,  $T_p = 3$  GeV, 500 ton, 40 m length, 40 m mid-baseline



# Thinking about experimental parameters

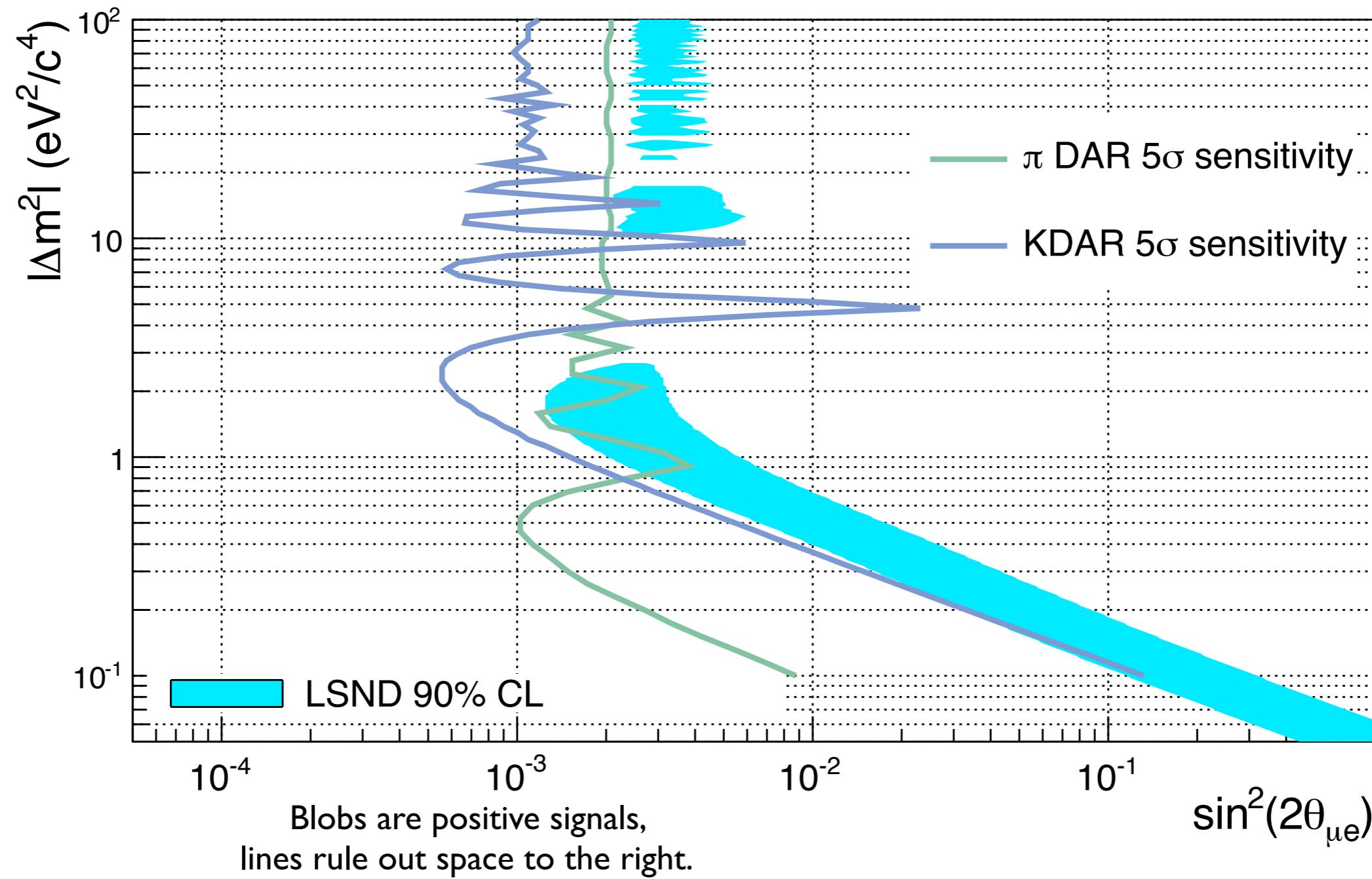
## Example 2:

A detector at a long distance ( $\sim 120$  m) from the target  
Advantages: optimized for KDAR; reduced beam-related background



(Sensitivity to  $\Delta m^2 \sim 1$  eV $^2$  is optimized at 40-60 m for piDAR and  $\sim 160$  m for KDAR)

Example 2:  
5 year, 1MW,  $T_p=3$  GeV, 500 ton, 20 m length, 120 m mid-baseline



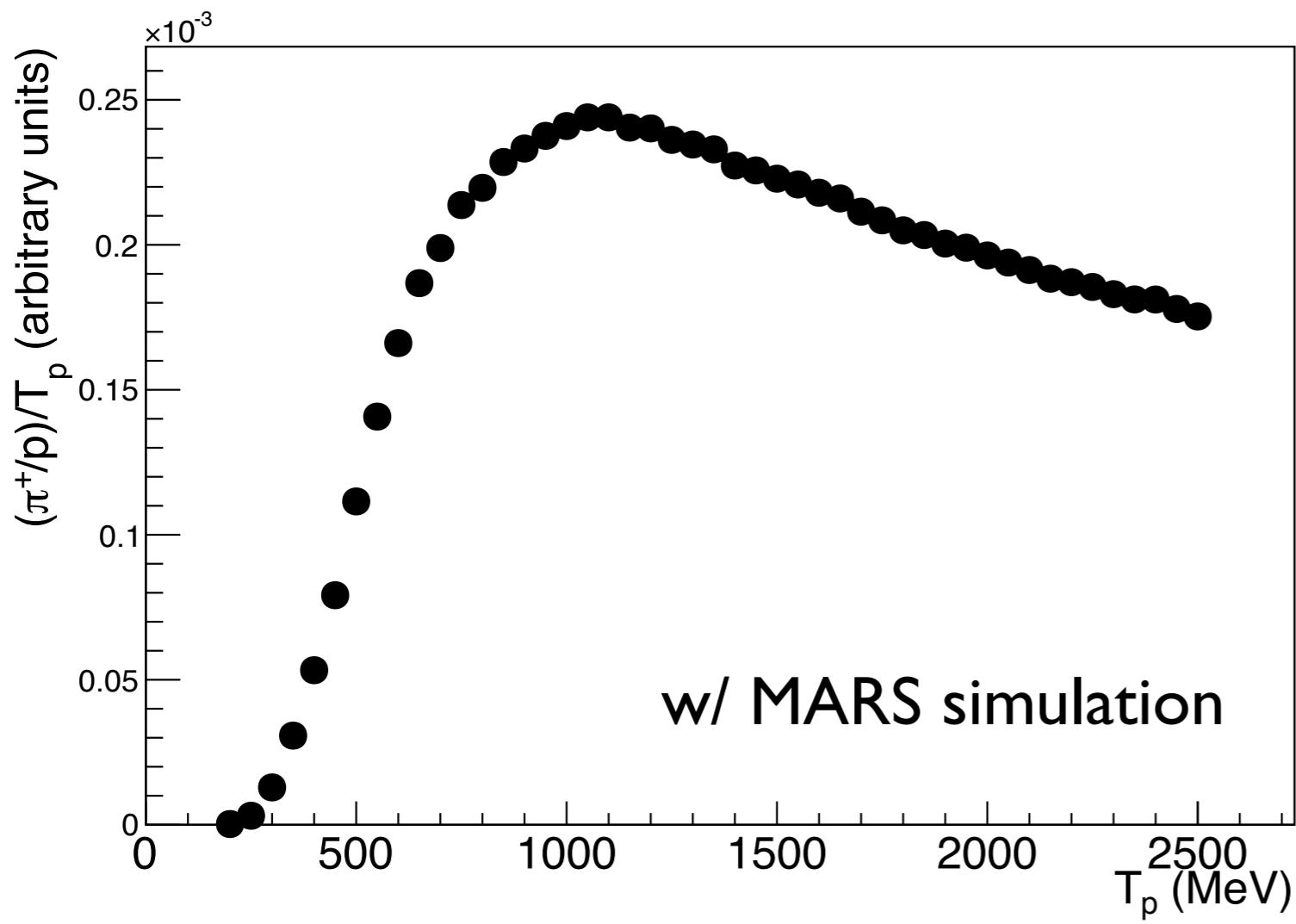
# A definitive probe

- piDAR+KDAR provides sensitivity to oscillations in multiple channels and with neutrino and antineutrino!
  - Discovery confidence (if it exists).
  - Precision measurements of sterile properties (if it exists).

# Outline

- Sterile neutrinos
- KDAR (kaon decay-at-rest)
- piDAR (pion decay-at-rest)
- Beam considerations for piDAR+KDAR

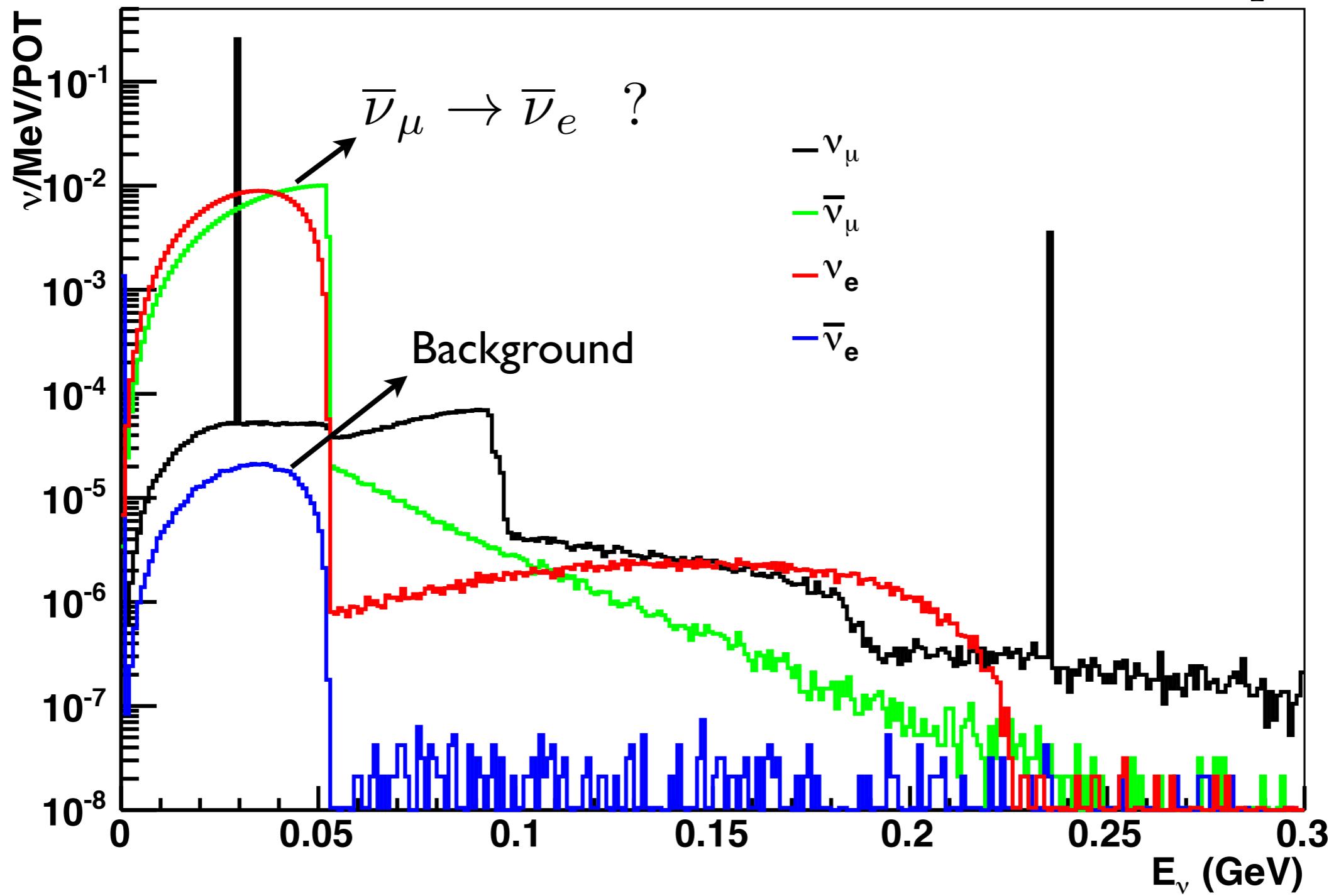
# Pion yield vs. proton energy



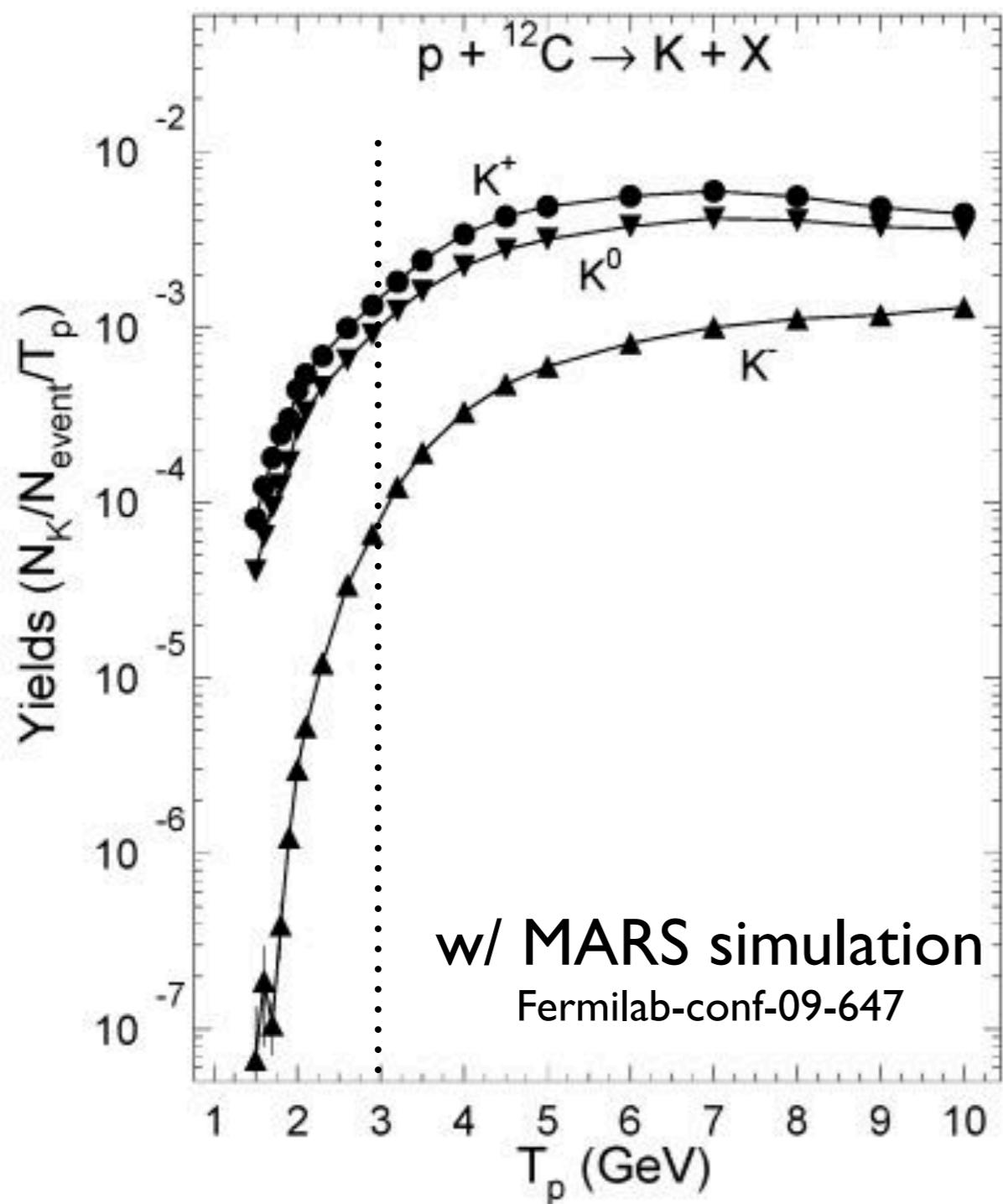
- piDAR is best with  $\sim 1$  GeV protons in consideration of production only.
- The  $\pi^+/\pi^-$  production ratio is also important to consider. We want to avoid producing  $\pi^-$  as  $\mu^-$  can produce intrinsic electron antineutrino background. The production ratio is most favorable at lower energies.
- Further, the target/dump should be high-Z in order to increase the chance of  $\pi^-/\mu^-$  capture (and reduce decay-induced intrinsic electron antineutrino background).

# piDAR

Detect with:  
 $\bar{\nu}_e p \rightarrow e^+ n$

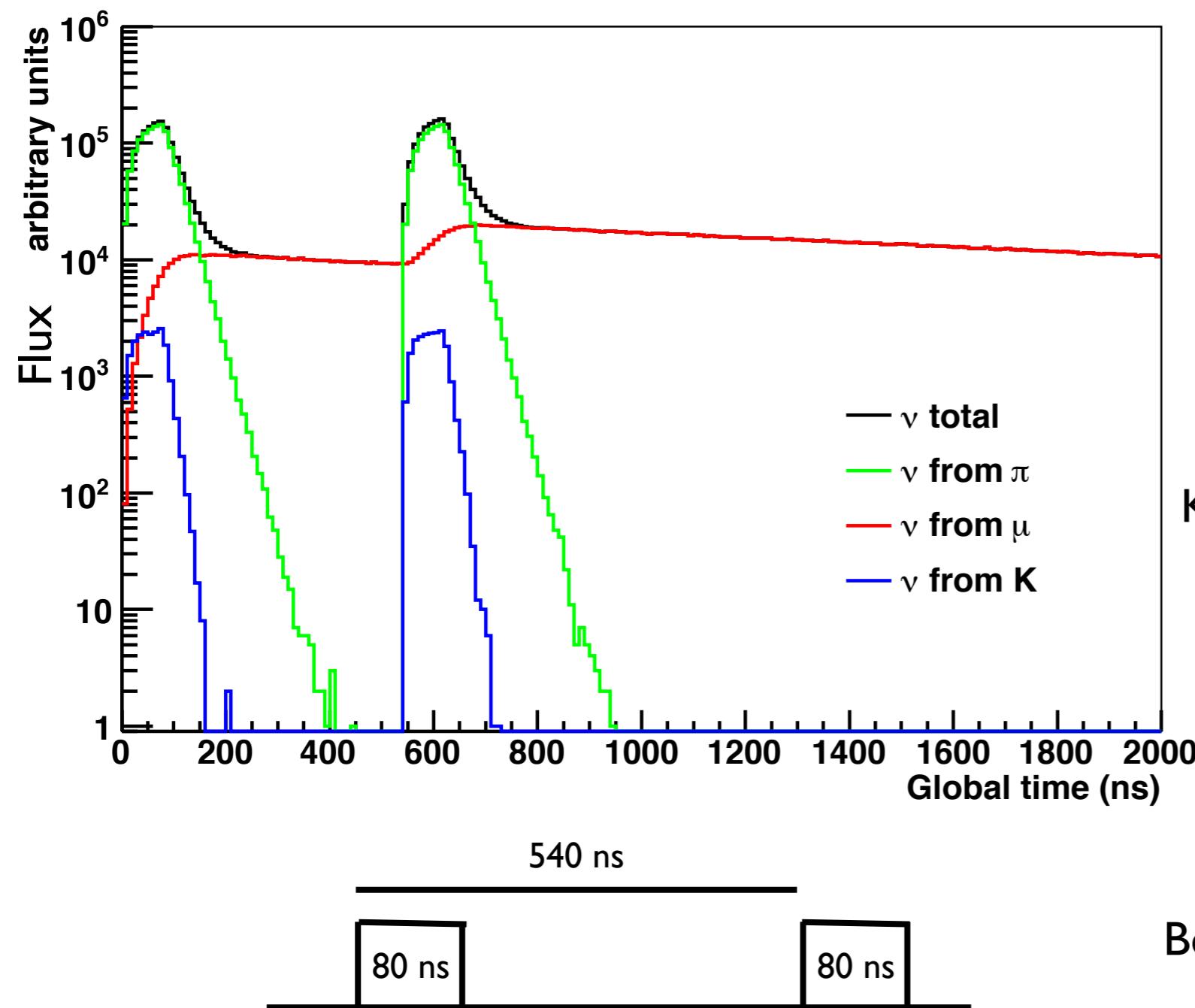


# Kaon yield vs. proton energy



- KDAR requires >3 GeV protons to get enough kaons per incoming proton.
- ~5-8 GeV is optimal.

# Example of beam timing: 3 GeV, IMW MLF facility in Japan



piDAR steady state background is reduced by  $\sim 1,000$  compared to LSND.

Allows separation of neutrinos from pion and muon.

KDAR steady state background is negligible.

# Conclusions

- Kaon decay-at-rest is a new idea to search for the sterile neutrino. A  $>3$  GeV proton source is required along with a lot of protons, a big detector, and strong energy resolution.
- KDAR can be combined with LSND-like pion/muon decay-at-rest in a single-detector-experiment for a sensitive sterile search with both neutrinos and antineutrinos and with both appearance and disappearance.
- I haven't even mentioned the other particle physics you could do with such a source: coherent scattering, non-standard neutrino interactions, weak mixing angle, neutron radius, supernova xsec, ...